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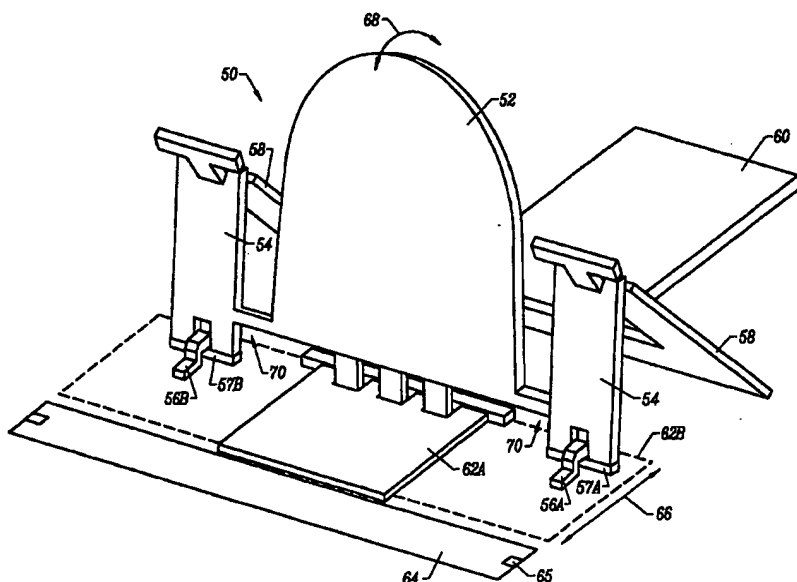
(57) Abstract

An optical scanning system includes a light source to generate a light beam and an oscillatory microelectromechanical system (50) including a mirror (52) that deflects the light beam in a predetermined manner. The light source and microelectromechanical system (50) are formed in a silicon substrate. Rotational shafts (70) in the microelectromechanical system facilitate oscillatory movement of the mirror (52).

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APPARATUS AND METHOD FOR OPTICAL SCANNING WITH AN
OSCILLATORY MICROELECTROMECHANICAL SYSTEM

Brief Description of the Invention

This invention relates generally to optical scanners. More particularly, this invention relates to a microelectromechanical system that operates as an oscillatory optical scanner.

5

Background of the Invention

This invention was made with Government support under Grant (Contract) No. DABT-63-95-C-0055 awarded by the Advanced Research Project Agency and Grant (Contract) No. ECS-9419112 awarded by the National Science Foundation. The

10   Government has certain rights to this invention.

Optical scanners are used for scientific and industrial applications ranging from laser imaging and displays to laser surgery tools and home-office appliances, such as facsimile machines and printers. Barcode optical scanners are used for automatic object-identification. Most optical scanners use a polygon mirror. Unfortunately, a

15   polygon mirror requires precision machining for the polygon surfaces to insure flatness and repeatability when the laser beam sweeps across the reflecting facets. In addition, a polygon mirror is relatively bulky. A polygon mirror can be considered a macroscopic device. As used herein, a macroscopic device is a device with a third dimension greater than approximately several milli-meters, where the third dimension

20   refers to the height above a horizontal substrate. A microscopic device is a device with a third dimension less than approximately several milli-meters.

Silicon-surface-micromachining technology has been used to fabricate microscopic devices. In particular, optical microelectromechanical systems (MEMS) have been implemented with movable-micromirrors. Figure 1 illustrates an optical MEMS 20 in accordance with the prior art. The optical MEMS 20 includes a MEMS
5   mirror assembly 22, which optically links a laser 24 to an optical fiber 26. A lens assembly 28 is positioned between the laser 24 and the MEMS mirror assembly 22.

Figure 2 is a more detailed illustration of a MEMS mirror assembly 22 that may be used with the apparatus of Figure 1. The MEMS mirror assembly 22 includes a mirror 30 positioned on a mirror slider 32 through the use of hinges 34. Hinges 34
10   are also used to couple the top of the mirror 30 to the top of a support 36. The bottom of the support 36 is connected to a support slider 38 through the use of hinges 34.

The support slider 38 includes support slider comb fingers 40, which are in an inter-digit arrangement with stator comb fingers 42. The combination of the support slider comb fingers 40 and the stator comb fingers 42 form a comb drive 43. As
15   known in the art, a comb drive uses capacitive charge between support slider comb fingers 40 and stator comb fingers 42 to alternately push the support slider 38 away from the stator comb fingers 42 or pull the support slider 38 toward the stator comb fingers 42. In this way, the mirror 30 can be fabricated within the horizontal plane of a semiconductor and then be lifted into a vertical configuration (third dimension) with
20   respect to the semiconductor, as shown in Figure 2. A comb drive may also be used in relation to the mirror slider 32 to facilitate this process.

Figure 3 illustrates a pin-and-staple hinge 34, which includes a staple portion 35 and a pin portion 37. The pin portion 37 forms a segment of mirror 30. The figure illustrates how the mirror 30 is allowed to pivot about the hinge 34, thereby allowing
25   the mirror 30 to be lifted from a horizontal plane of a semiconductor surface and into a vertical plane with respect to the semiconductor surface.

MEMS mirror assemblies of the prior art have been limited to relatively slow mirror movement. That is, the comb drives have been used to slightly modify an initial mirror position. Thus, MEMS mirror assemblies of the prior art have not been
30   used for scanning. In other words, prior art MEMS mirror assemblies have not been used to rapidly traverse a range of positions in a coordinate axis. In the absence of this capability, the utility of MEMS in optical systems is limited. Accordingly, it would be highly desirable to provide a MEMS suitable for optical scanning operations. Such a

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device could thereby operate as a building block in a variety of opto-electrical equipment.

Summary of the Invention

5   The optical scanning system of the invention includes a light source to generate a light beam. An oscillatory microelectromechanical system including a mirror deflects the light beam in a predetermined manner. The light source and microelectromechanical system are formed on a silicon substrate. Rotational shafts in the microelectromechanical system facilitate oscillatory movement of the mirror.

10   The device of the invention is on a microscopic scale, thus it is compact and extremely light weight. The power consumption of the device is minimal. High precision positioning over a large angular range makes the invention suitable for a variety of optical applications, such as laser scanners and printers, displays, holographic-data storage, and fiber-optic switches.

15   The device of the invention can be packaged in vacuum or hermetically sealed to reduce air damping, mirror deformation and particulate erosion of the mirror surface. The mechanical Q-factors of the scanners have been found to increase significantly even under a moderate vacuum. The device of the invention can be produced inexpensively because it can be batch-fabricated.

20

Brief Description of the Drawings

For a better understanding of the nature and objects of the invention, reference should be made to the following detailed description taken in conjunction with the accompanying drawings, in which:

25   FIGURE 1 is a perspective view of an optical MEMS system in accordance with the prior art.

FIGURE 2 is a perspective view of a MEMS mirror assembly in accordance with the prior art.

FIGURE 3 is a perspective view of a hinge and mirror combination in

30   accordance with the prior art.

FIGURE 4 is a perspective view of an optical scanning resonant MEMS in accordance with an embodiment of the invention.

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FIGURES 5A-5B illustrate the movement of torsion bars of the optical scanning resonant MEMS of Figure 4.

FIGURE 6 is a more detailed illustration of a torsion bar of Figure 5B.

FIGURE 7 is a perspective view of an optical scanning resonant MEMS in
5   accordance with another embodiment of the invention.

FIGURES 8-19 illustrate processing steps leading to the construction of an optical canning resonant MEMS in accordance with an embodiment of the invention.

FIGURE 20 illustrates an optical interferometric measurement apparatus used to test the device of the invention.

10 FIGURE 21 illustrates a typical output signal when a device of the invention is driven on resonance with a 20-V sinusoidal voltage.

FIGURE 22 illustrates the amplitude and phase frequency response of an optical scanning resonant MEMS of the invention.

FIGURE 23 illustrates the optical scanning resonant MEMS of the invention
15 incorporated into a barcode reading system.

FIGURE 24 illustrates a barcode signal detected with a device of the invention.

FIGURE 25 illustrates multiple optical scanning resonant MEMS used in a multi-axis optical system, such as a raster scanning display.

Like reference numerals refer to corresponding parts throughout the several
20 views of the drawings.

Detailed Description of the Invention

Figure 4 is a perspective view of an optical scanning oscillatory MEMS 50 in accordance with an embodiment of the invention. The device 50 includes a mirror 52
25 connected to a frame support 54. Hinges 56A, 56B interlock with the frame support 54. A mirror lift support 58 is connected at the top of the frame support 54. A mirror lift support slider 60 is connected to the base of the mirror lift support 58.

A mirror slider 62A is connected to the mirror 52. A comb drive 64 is connected to the mirror slider 62A. The comb drive 64 forces the mirror slider 62A
30 back and forth along the axis marked by arrow 66. This, in turn, causes the mirror 52 to rotate front-to-back, as shown with arrow 68. This front-to-back motion can be thought of as lifting the mirror 52 in and out of the plane defined by the mirror frame support 54.

A key distinguishing feature of the device 50 is that it operates in an oscillatory mode. That is, the device 50 is configured such that it regularly traverses through a predefined path. In certain embodiments of the invention, the oscillatory device 50 resonates. That is, the device 50 is configured such that it has a natural vibration

5 frequency that coincides with an applied vibrational force from the comb drive 64. The oscillatory and/or resonant operation of the device 50 allows the mirror 52 to rapidly move, thereby making it suitable for optical scanning operations.

The oscillatory motion of the mirror 52 may be achieved by moving the entire mirror slider 62. Figure 4 illustrates, in phantom, a mirror slider 62B that supports

10 hinges 56A, 56B. As shown with arrow 66, the entire mirror slider 62 may be moved by the comb drive 64. The prior art has used relatively large mirror sliders such as 62B, however, such mirror sliders have not been used in an oscillatory mode.

In a preferable embodiment, the mirror 52 is only attached to the mirror slider 62A and the hinges 56A, 56B are fixedly attached to a substrate. In such an

15 embodiment, rotational movement of the mirror 52 is achieved through torsion bars 70. The torsion bars 70 are a type of rotational shaft. Observe that each hinge 56 secures a pin 57 of the mirror frame support 54. The pins 57 also constitute a type of rotational shaft.

Figure 5A illustrates torsion bars 70 connected between a mirror 52 and mirror

20 frame support segments 54. In Figure 5A, the mirror is in the horizontal plane defined by the mirror frame support 54. In Figure 5B, the mirror is twisted into a plane that is perpendicular to the horizontal plane defined by the mirror frame support 54. Region 72 of Figure 5B illustrates how the torsion bars 70 support this twisting motion. Figure 6 is an enlarged view showing the twisting action of the torsion bar 70.

25 Figure 7 is a perspective view of an optical scanning resonant MEMS 80 constructed in accordance with an alternate embodiment of the invention. The device 80 includes a mirror 82 supported by a mirror frame support 84. Hinges 86 are used to attach the mirror frame support 84 to a substrate. A mirror lift support 88 is attached to the mirror frame support 84. A mirror lift support slider 90 is attached to the mirror

30 lift support 88. A mirror slider 92 is attached to the mirror 82. A comb drive (not shown) pushes or pulls the mirror 82, allowing it to rotate on torsion bars 94. The resultant motion is illustrated with arrows 96. The mirror 82 moves in and out of the plane defined by the mirror frame support 84. In particular, the left and right sides of

the mirror 82 move in and out of the plane defined by the mirror frame support 84. This embodiment is in contrast to the embodiment of Figure 4 where the top and bottom of the mirror 52 move in and out of the plane defined by the mirror frame support 54. The embodiment of Figure 7 can be used for X-axis scanning, while the

5   embodiment of Figure 4 can be used for Y-axis scanning.

In one embodiment, the mirror 52 of Figure 4 is implemented as a 200 by 250 micro-meter device. The electrostatic comb drive for the system is implemented with 100 interdigitated fingers for both the rotor and the stator on the two sides, with lateral dimensions totaling 1 mm. The comb drive motor may be attached to the mirror slider

10 62 through a pair of restoring springs. In one embodiment, the folded restoring springs are trusses composed of four 300 micron long beams, each having a 4 micron square cross-section. The maximum excursion of the rotor comb from its rest position is determined by the length of the comb fingers which, in this design, is limited to 20 micro-meters. At 150 micro-meters away from the mirror shaft, this 20 micro-meter

15 displacement results in a 7.6 degree rotation of the mirror. In other words, the maximum scan angle of this resonant structure is approximately 15 degrees (30 degree optical) if driven on resonance with a sufficiently large ac voltage applied to an input node 65 of the comb drive 64. This scan angle compares well with typical performance characteristics obtained in macroscopic resonant scanners.

20 Figures 8-19 illustrate the processing sequence used to fabricate an optical scanning oscillatory MEMS. On top of the polysilicon ground plane which was common to the electrostatic combdrives, three layers of structural polysilicon (each 2 micrometers thick) were laid down to construct the scanning micromirrors. Low-pressure chemical-vapor deposition (LPCVD) of phosphosilicate glass (PSG) was used

25 as the sacrificial material separating the different polysilicon layers. The PSG was also used as the hard mask for the structural polysilicon layers when they were etched in chlorine-based plasma for pattern definition.

The silicon substrate was first passivated by successive layers of LPCVD thermal silicon dioxide and silicon nitride. A 0.5 micrometer-thick film of in situ

30 phosphorous-doped LPCVD polysilicon was then deposited and patterned to form the ground plane for the electrostatic comb motor. Figure 8 illustrates a polysilicon ground plane 100 on a Si_3N_4 base 102. Figure 9, taken along the line 9-9 of Figure 8,

illustrates the polysilicon ground plane 100, the Si_3N_4 base 102, an SiO_2 104 layer, and a silicon substrate 106.

A thick (2 micrometer) layer of sacrificial LPCVD PSG was then deposited. Indentations were wet-etched with 5:1 hydrofluoric acid (HF) on the PSG surface to create dimples in the subsequent polysilicon layer. The dimples reduce the surface-contact area and, therefore, the "stiction" between the two surfaces. Openings were also etched in the PSG by a fluorine-based (CF4) plasma so that the next polysilicon layer can be anchored to the substrate or to the polysilicon ground plane.

The first structural polysilicon layer was then deposited and patterned to form the combdrives, back supports, sliders and the bottom plate of the hinge structures. Figure 9 illustrates a polysilicon region 108 forming the movable comb and a polysilicon region 110 forming the stationary comb. The corresponding cross-sectional view of this structure is shown in Figure 11.

Another layer of sacrificial PSG was deposited, and again openings were dry etched to make the anchors of the guides out of the second structural polysilicon layer. A pin structure was also formed in this polysilicon layer. Figure 12 illustrates a pin structure 112 formed from the second structural polysilicon layer. Figure 13 is a corresponding cross-sectional view. Figure 14 illustrates openings 114 that are subsequently used to form staple posts. Figure 15 is a corresponding cross-sectional view.

The final structural polysilicon layer was deposited on top of the third sacrificial PSG layer, and the body of the mirror and the staples of the pins for the hinge structures were formed in it. Figure 16 illustrates a staple structure 116 and mirror 118 formed from the final structural polysilicon layer. Figure 17 is a corresponding cross-sectional view.

The last step was etching through-holes in the larger polysilicon areas to reduce the final wet-etching time in concentrated HF used to release the mechanical parts. Once the sacrificial PSG was removed, the released polysilicon layers can be removed and the structures assembled. Figures 18 and 19 illustrate the released mirror 118.

Increasingly thicker (up to 7 micrometers) layers of photoresist were used to accommodate the large topographical step heights. As a result, polysilicon "stringers" can form around the polysilicon structures. Over etching of the polysilicon layers alleviates the stringer problem. If stringers remain after the fabrication is completed, a

timed etch in 10:1 HF to dissolve the PSG that holds the stringers can be used to remove them before the final release step.

It is possible to simplify the fabrication process using only three layers (two structural layers) of polysilicon with alternative hinge designs. The pin-and-staple microhinges have been replaced by torsion bars serving as the rotation shaft and by cross-weaving polysilicon stripes for the connecting and assembly hinges. Using torsion or flexing hinges also reduces the errors introduced from the bearing friction in the pin and staple configuration.

The dynamic response of the optical scanning oscillatory MEMS of the invention has been characterized using an interferometric apparatus 130 as depicted in Figure 20. A laser beam from a single-mode 1.3 micro-meter DFB laser diode 132 is coupled into a single-mode fiber 136 with a 3 dB coupler 138 that splits the beam between two output ports. The optical scanning oscillatory MEMS 50 is placed in front of one of the outputs, so that the top part of the mirror 52 and the fiber end-facet forms a Fabry-Perot interferometer. The other output of the splitter is used to monitor the laser power level via diode 140. Light reflected from the etalon and coupled back into the fiber is detected by a photodiode 142. Varying-frequency sinusoidal voltage waveforms (20V in amplitude) are applied to the comb drive 64.

A typical interference pattern is shown in Figure 21. Recorded when a 1.5 kHz ac voltage is applied to the comb motor (i.e. when the micromirror is resonating at 3 kHz), the trace in Figure 21 shows that the tip of the scanning micromirror sweeps across more than 23 cycles of constructive and destructive interference. With the laser wavelength of 1.3 micro-meters, this corresponds to approximately 15 micro-meters of displacement for the top end of the mirror 52. In other words, when the electrostatic-comb motor 64 is ac-driven on resonance with a sinusoidal voltage of 20 V in amplitude, the mirror 52 can deflect the laser beam by almost 12° in angle.

Plotted in Figure 22 is the large-signal frequency response of the optical scanning oscillatory MEMS 50. Resonating at 3 kHz with a system Q-factor of 2.8, the device has a maximum-optical-scan angle measured to be 28°. The dotted curve shows the theoretical model of a forced-damped-oscillation with a damping force proportional to the linear velocity of the moving parts in the mechanical system. The hump around 1.5 kHz in the measured curve is due to the second harmonic of the ac voltage (a dc bias voltage is applied in addition to the ac voltage).

To demonstrate barcode scanning using the optical scanning resonant MEMS 50, the apparatus of Figure 23 was constructed. The apparatus includes a laser 150, objective lens 152, an optical scanning oscillatory MEMS 50, a barcode object 154, a photodetector with a collecting lens 156, and a signal processing device 158.

5   Elements 150, 152, 50, and 156 are fabricated on a silicon substrate 157. The signal processing device 158 may also be implemented in the silicon substrate 157. The signal processing device 158 may also be implemented as a microprocessor and related software. Regardless of the implementation, the following signal processing operations are performed.

10   For simplicity, the post-objective scanning scheme is adopted so that no $f\theta$-filled-flattening lens is needed. The distortion introduced by mapping a nonplanar image plane to a flat image surface (the barcode) is not a concern as long as the depth-of-field of the optical system is sufficiently long such that the spot size at the barcode is always small enough to resolve the thinnest bars.

15   The scanning speed of the resonant scanner 50 varies in a sinusoidal fashion. Consequently, the detected signal as a function of time does not correspond to the bar widths and spacings in a straight-forward manner. However, the lack of correspondence can be compensated by considering the following.

The motion of a scanner operating at mechanical resonance is:

20

$$\theta = \theta_s \sin (\omega t) \qquad \text{(Equation 1),}$$

where θ is the scanner (mirror) angle, θ_s is the maximum excursion angle, and ω is the angular resonance frequency. It follows that:

25

$$\delta\theta/\delta t = \omega\theta_s \cos (\omega t) \qquad \text{(Equation 2).}$$

When a laser beam is reflected off the surface of the scanning mirror, the linear displacement x in the image plane is:

30

$$x = S \tan (2\theta) \qquad \text{(Equation 3),}$$

9

where S is the distance from the scanner mirror to the image plane (a constant for a flat image plane). Therefore,

$$\delta\theta/\delta t = 2S(1 + \tan^2 2\theta)\delta\theta/\delta t \qquad \text{(Equation 4)}.$$

5

Substituting equation (1) into (3) gives the relation between the linear displacement with time which can be used to translate the detected time signal into a spacial equivalent. Alternately, the combination of equations (2) and (4) relates the angular velocity of the scanner to the linear scan rate of the laser beam.

10   Figure 24 illustrates a barcode object 154 that is processed using the apparatus of Figure 23. A 1.5 mw red He-Ne laser is used as the laser 150. The backscattered light from the barcode is received by the photodetector/collecting lens 156. Figure 24 shows the recorded signal and the reconstructed black-and-white pattern corresponding to the scanned barcode symbol, as generated by the signal processing device 158.

15   The single-mirror scanners of Figures 4 and 7 can be combined to form a more complicated system as shown in Figure 25. A first optical scanning oscillatory MEMS 176 is used to scan in-plane (X-axis) while a second optical scanning oscillatory MEMS 178 is used to scan out-of-plane (Y-axis). A light source (a laser diode or a LED) 172 and microlenses 174 are integrated on a silicon substrate 179. The reflected

20 light is deflected by a stationary mirror 177 to a projection device 180. The apparatus of Figure 25 can be used either as a studio projector or for direct viewing such as those used in headsets. The two-mirror, two-axis raster scanner of Figure 25 finds a wide range of applications also in areas such as communications, medicine, and entertainment, to name a few.

25   Returning to Figure 23, shown, in phantom, is a vacuum package 190 for the optical scanning oscillatory MEMS 50. The vacuum package alleviates the adverse effect from the atmospheric air, such as the effect of air turbulence on mirror deformation and damping, the erosion of the mirror surface, and the vibrational and temperature instability of the resonance response. Moreover, lowering air-pressure

30 increases significantly the Q-factor for those systems in which air drag is the main source of damping. This leads to an even higher mechanical performance (e.g., larger scan angle with the same driving voltage) and potentially better reliability for the

oscillatory microscanner system. Vacuum packaging is very difficult and costly in macroscopic systems.

The unique silicon microhinge technology allows the creation of high-aspect-ratio optical surfaces with dimensions in the hundreds of micro-meters, essential for

5   higher image/spot resolution, while taking advantage of the planar integrated-circuit processing technology. Note that the optical axes of the optical devices, e.g., the micromirrors and the microlenses, are fabricated perpendicular to the silicon substrate (after assembly, the optical axes of the system are parallel to the silicon substrate). The advantages of this are legion. For example, it enables the full integration of the

10   laser diode and the other micromechanical devices on the same silicon chip, such that packaging is much easier. Thus, no investments in expensive equipment and no special processes are required. Instead, standard silicon integrated-circuit processing facilities may be exploited.

The invention has been described in reference to specific examples. Obvious

15   improvements upon the examples may be made. For example, by simply moving the rotational axis of the micromirror closer to its bottom, a larger scan-angle can be obtained while the rest of the scanner structure remains unchanged. The scan-angle can also be improved by lengthening the comb fingers, which increases the range of the rotor excursion.

20   The foregoing description, for purposes of explanation, used specific nomenclature to provide a thorough understanding of the invention. However, it will be apparent to one skilled in the art that the specific details are not required in order to practice the invention. In other instances, well known circuits and devices are shown in block diagram form in order to avoid unnecessary distraction from the underlying

25   invention. Thus, the foregoing descriptions of specific embodiments of the present invention are presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, obviously many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the

30   principles of the invention and its practical applications, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the following Claims and their equivalents.

11

IN THE CLAIMS:

1.   An optical scanning system, comprising:
        a light source to generate a light beam; and
5   an oscillatory microelectromechanical system including a mirror to deflect said
light beam in a predetermined manner.

2.   The apparatus of claim 1 wherein said light source and said oscillatory
microelectromechanical system are formed on a silicon substrate.
10
3.   The apparatus of claim 1 wherein said light source is a laser.

4.   The apparatus of claim 1 wherein said light source is a light emitting diode.

15   5.   The apparatus of claim 1 wherein said oscillatory microelectromechanical
system includes
        a mirror frame support; and
        rotational shafts positioned between said mirror frame support and said mirror.

20   6.   The apparatus of claim 5 wherein said oscillatory microelectromechanical
system includes
        a comb drive; and
        a mirror slider positioned between said mirror and said comb drive.

25   7.   The apparatus of claim 6 wherein said comb drive forces said mirror slider
against said mirror to cause said mirror to rotate with respect to said rotational shafts.

8.   The apparatus of claim 7 wherein said comb drive includes an input node to
receive a voltage signal.
30
9.   The apparatus of claim 1 further comprising a collecting lens and a signal
processing device, said collecting lens receiving a reflected barcode signal and said

signal processing device converting said reflected barcode signal from a time signal into an equivalent spacial signal.

10.   The apparatus of claim 1 further comprising a collecting lens and a signal
processing device, said collecting lens receiving a reflected barcode signal and said signal processing device converting said reflected barcode signal from a scanner angular velocity signal to a light beam linear scan rate signal.

11.   The apparatus of claim 1 further comprising a second oscillatory
microelectromechanical system including a second mirror to deflect said light beam in a predetermined manner.

12.   The apparatus of claim 11 further comprising a projection device.

13.   The apparatus of claim 1 further comprising a vacuum package surrounding said oscillatory microelectromechanical system.

14.   A method of optical scanning, said method comprising the steps of:
        generating a light beam;
        operating a mirror of a microelectromechanical system in an oscillatory mode;
        deflecting said light beam in a first direction with said microelectromechanical system.

15.   The method of claim 14 further comprising the step of deflecting said light
beam in a second direction with a second microelectromechanical system.

16.   The method of claim 15 further comprising the step of processing said light beam at a projection device.

17.   The method of claim 14 wherein said operating step includes the step of applying a voltage to said microelectromechanical system.

18.   The method of claim 14 further comprising the step of converting a reflected barcode signal from a time signal into an equivalent spacial signal.

19.   The method of claim 14 further comprising the step of converting a reflected
5   barcode signal from a scanner angular velocity signal to a light beam linear scan rate signal.
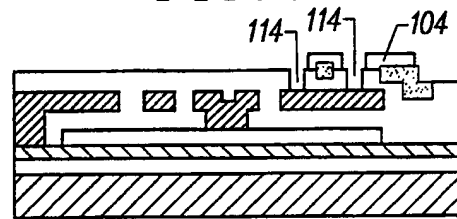
FIG. 1

(Prior Art)

FIG. 2
(Prior Art)

FIG. 3
(Prior Art)

FIG. 4

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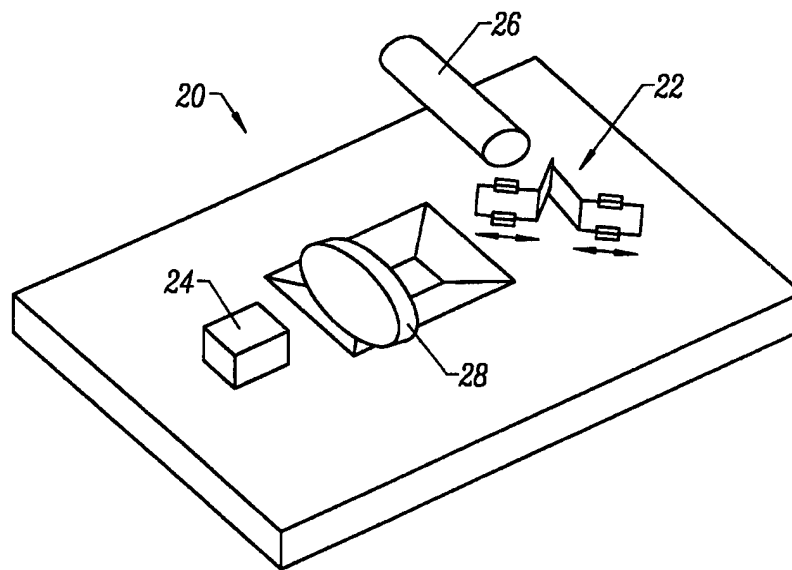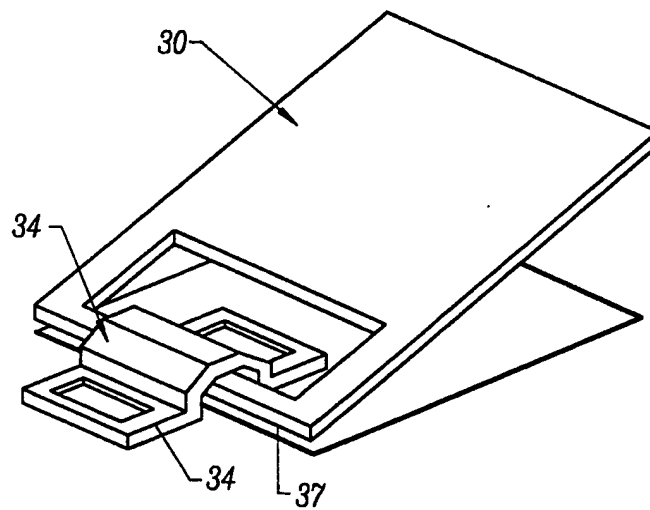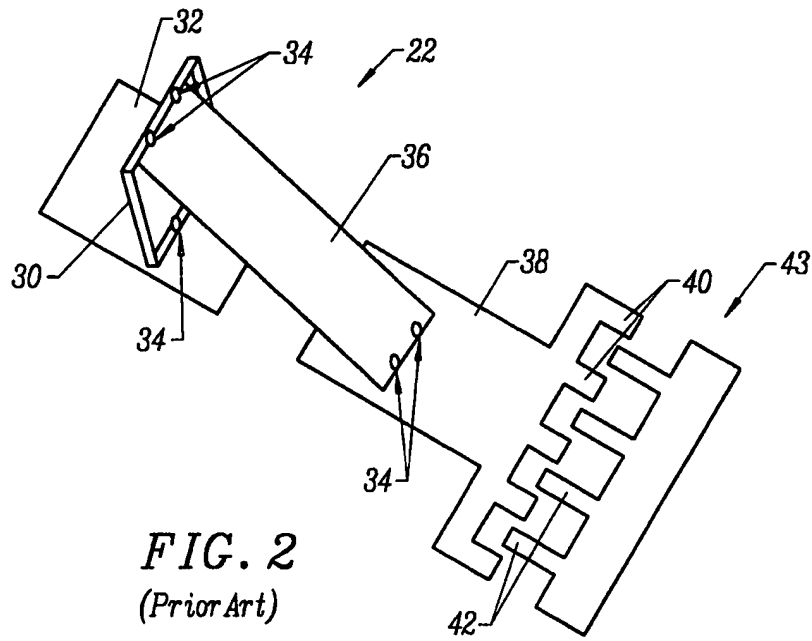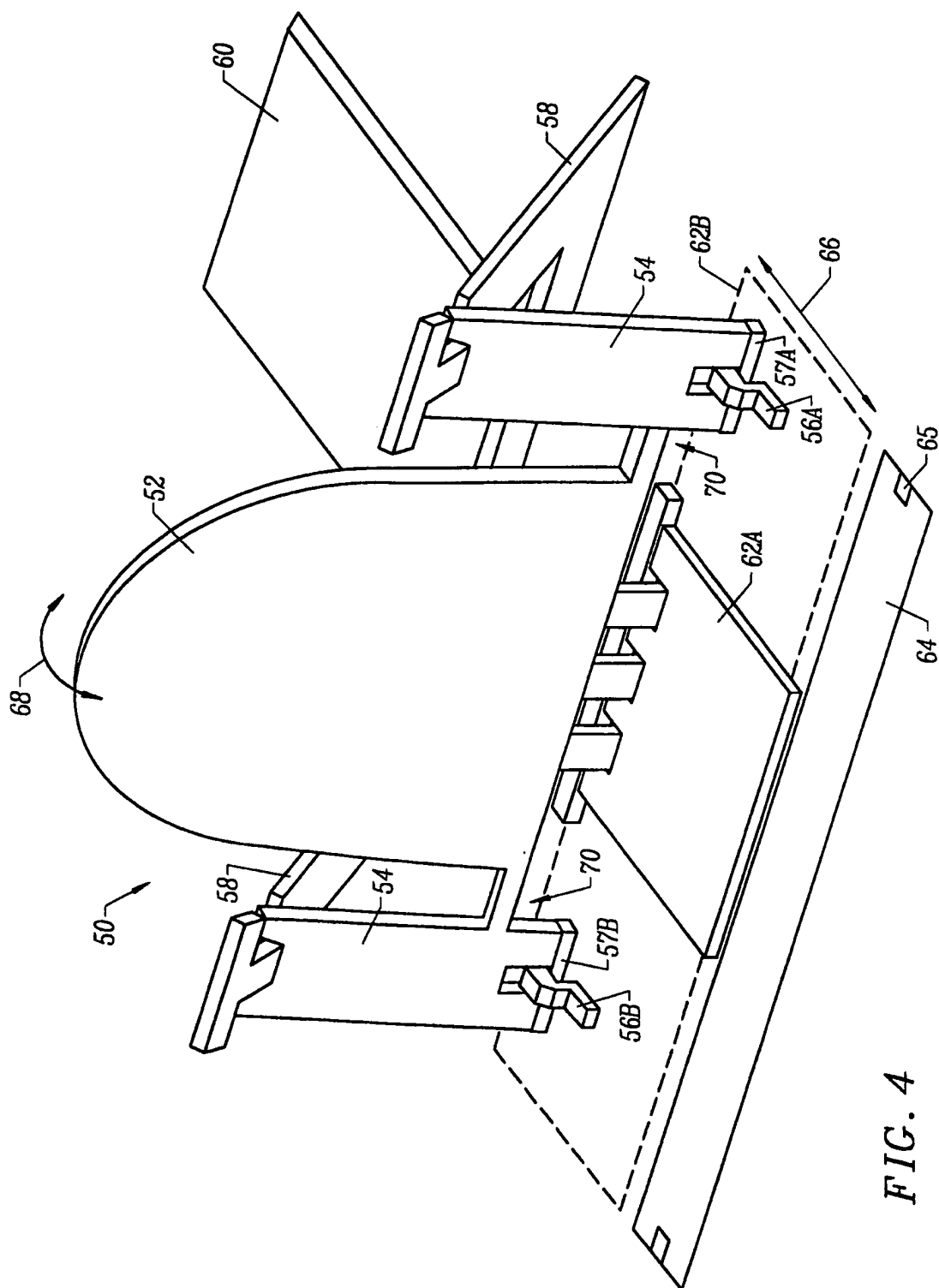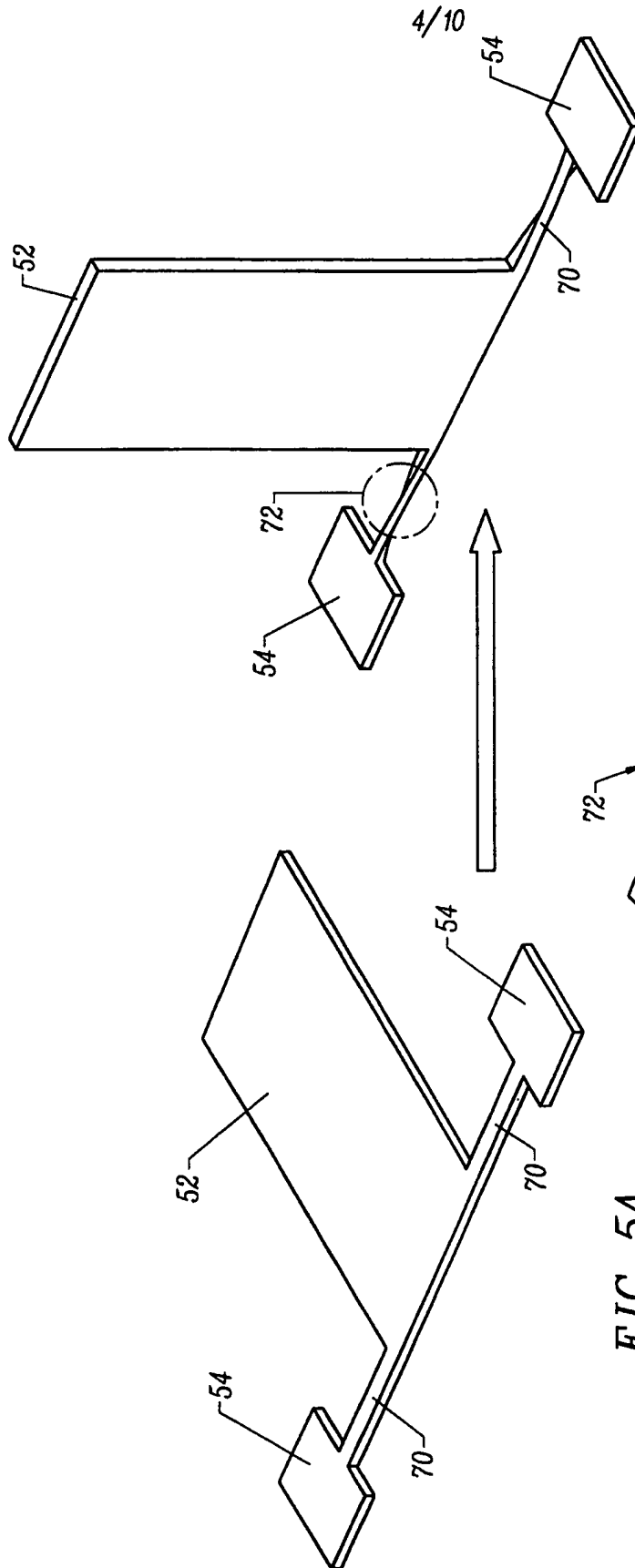
FIG. 5B

FIG. 5A
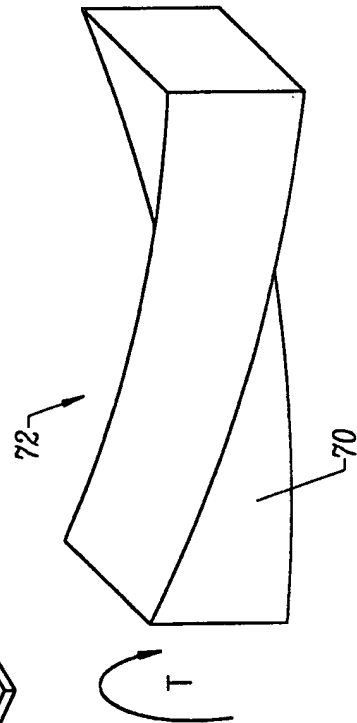
FIG. 6
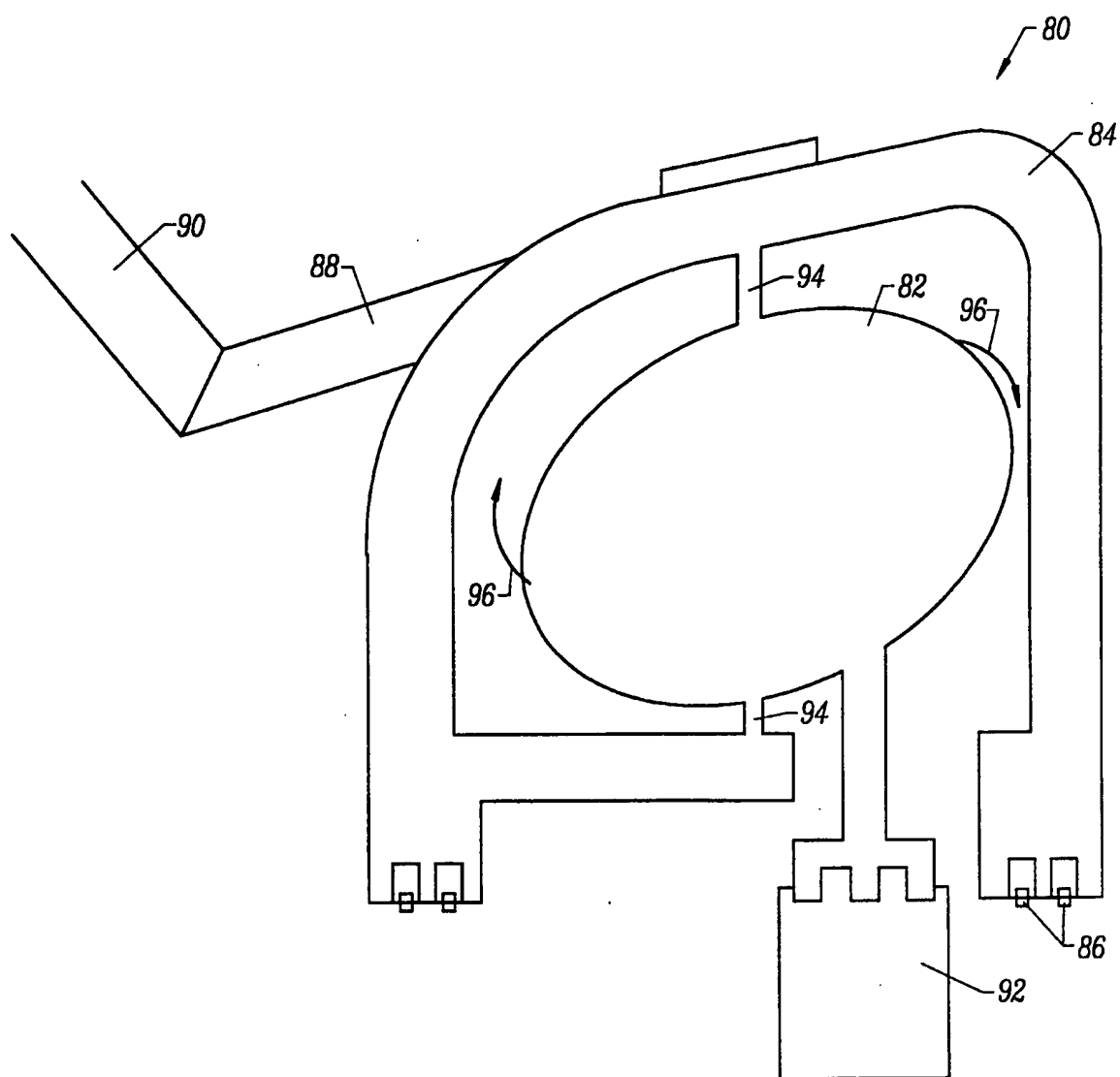
FIG. 7
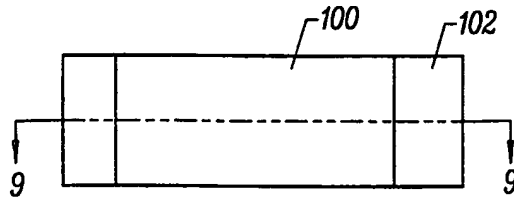
FIG. 8
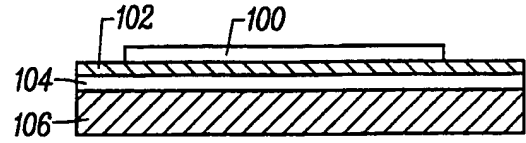
FIG. 9
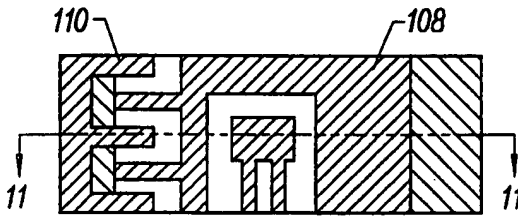
FIG. 10
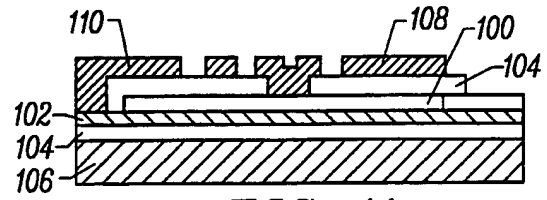
FIG. 11
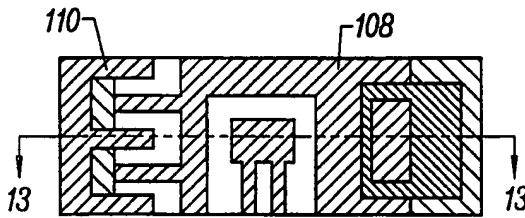
FIG. 12
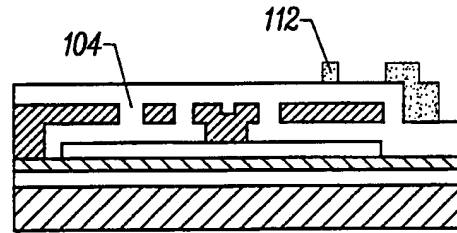
FIG. 13
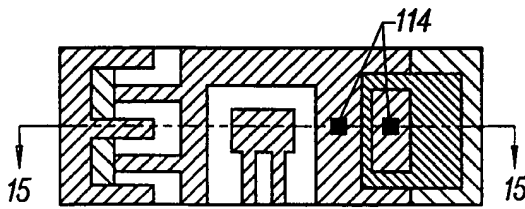
FIG. 14

FIG. 15
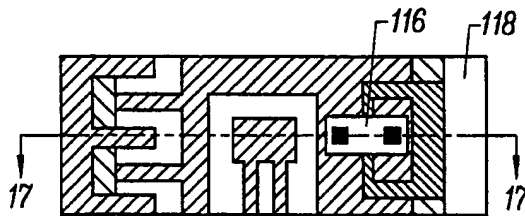
FIG. 16
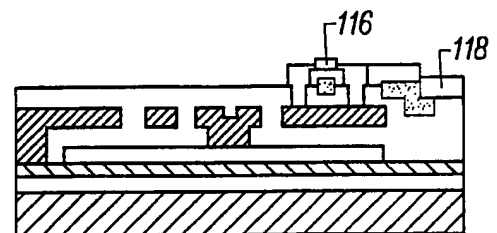
FIG. 17
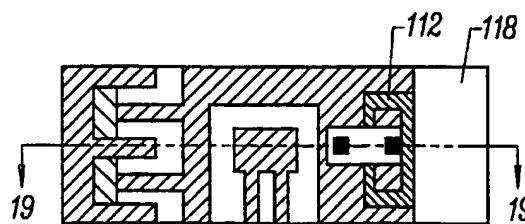
FIG. 18
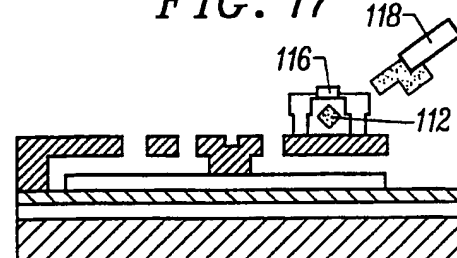
FIG. 19
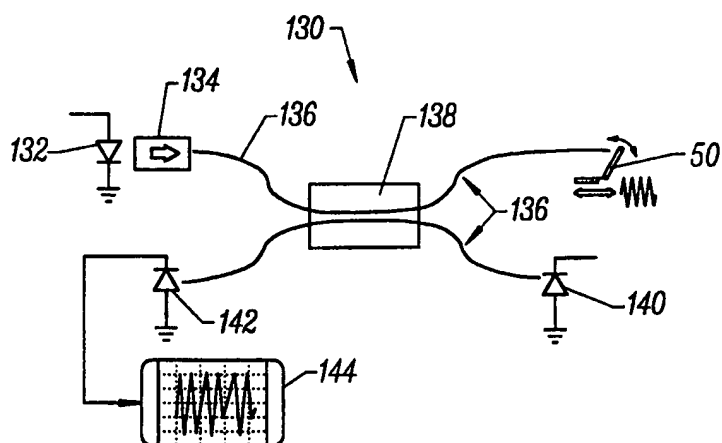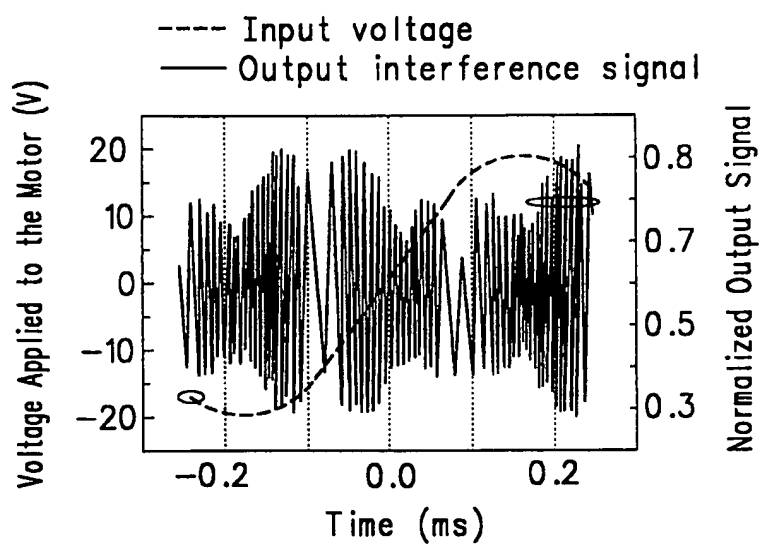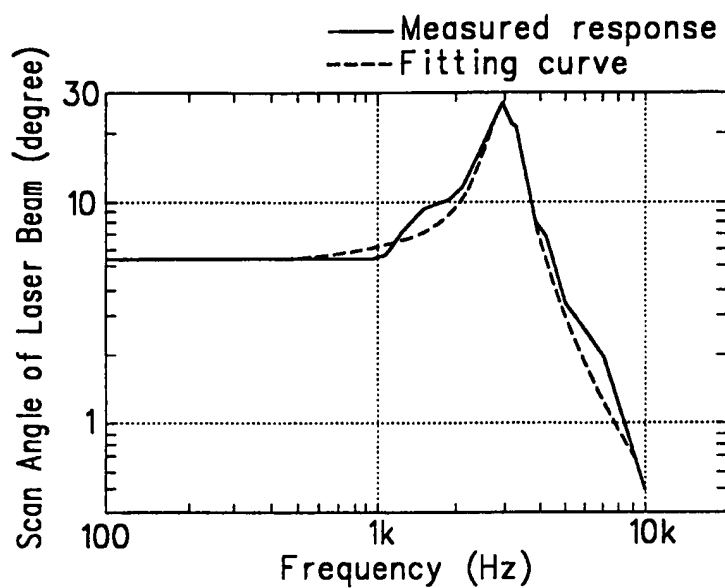
FIG. 20

FIG. 21

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FIG. 22
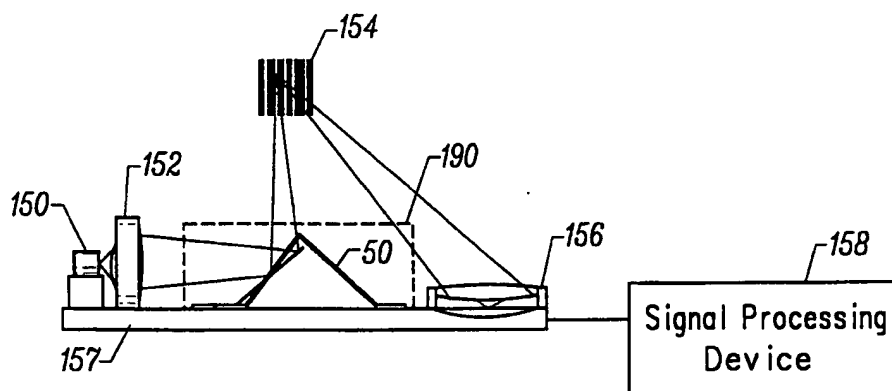
FIG. 23
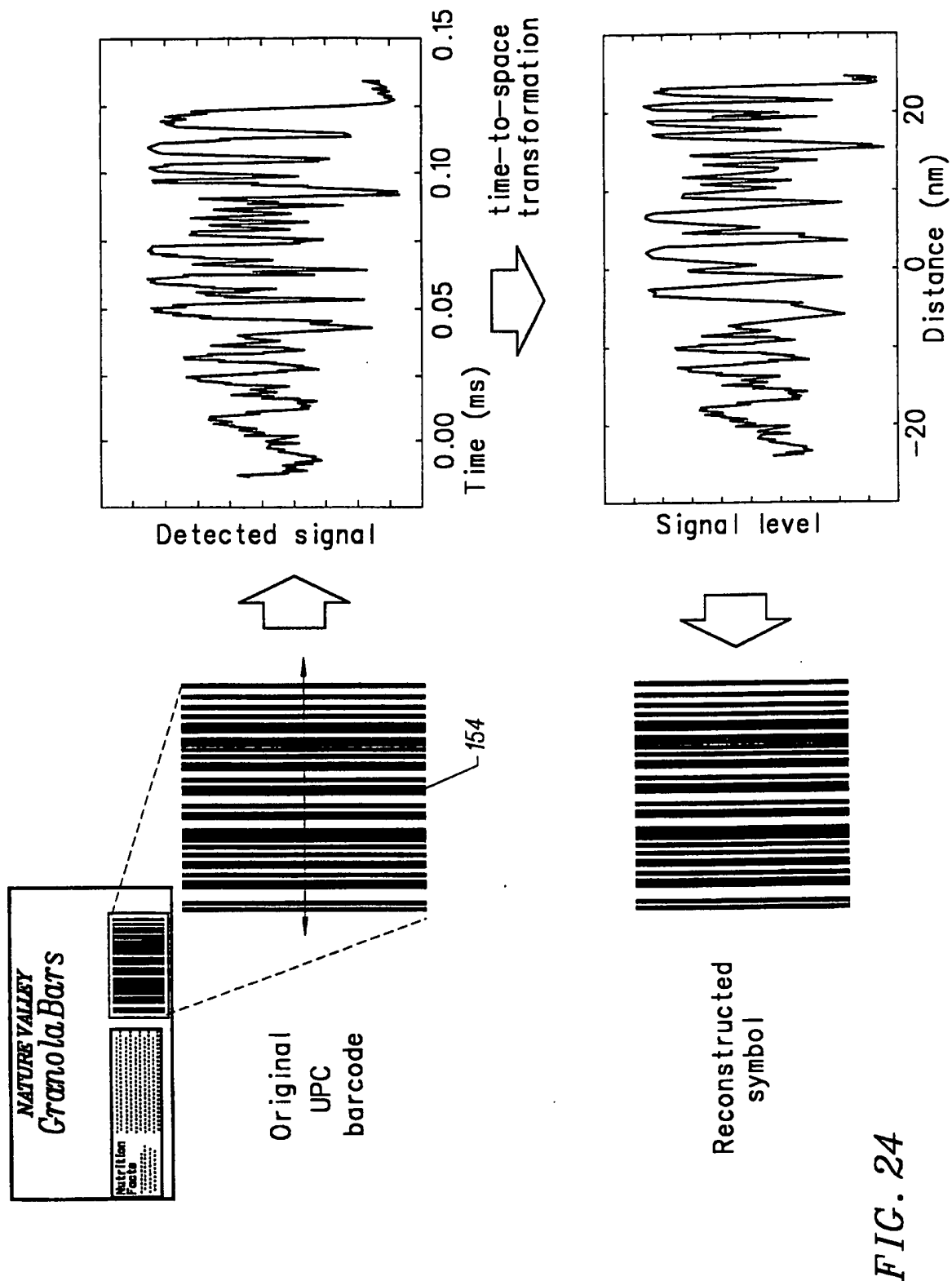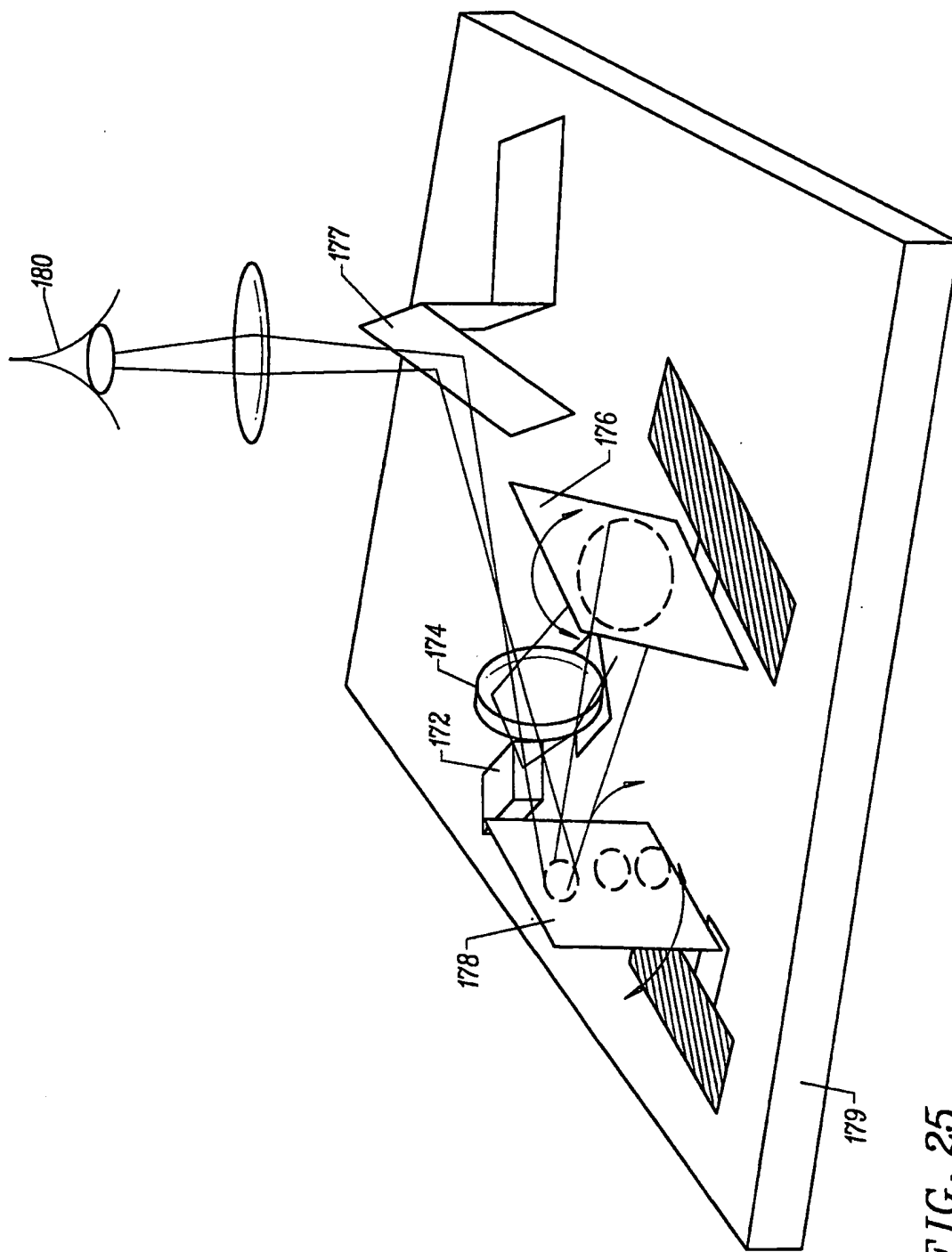
FIG. 24

FIG. 25

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6)   :G02B 26/08
US CL   :359/198-199, 201, 213-214, 224; 235/462
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. :   359/198-200, 201, 212-215, 223-225; 235/462

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 4,317,611 A (PETERSEN) 02 March 1982, (02/03/82) Figs. 1 and 8 and the accompanying text.	1, 3-5, 11, 14-15, 17 ------------ 9-10,13,16, 18-19
X ---- Y	KIANG ET AL Silicon-Micromachined Micromirrors with Integrated High-Precision Actuators for External-Cavity Semiconductor Lasers, IEEE Photonic Technology Letters, January 1996. Vol 8, No. 1, pages 95-97, see whole document.	1-8, 12, 14, 17, ----------- 9-10, 13, 18-19
Y	US 5,408,352 A (PENG) 18 April 1995, (17/04/95) Fig. 1 and column 6, lines 25-28.	9-10, 13, 16, 18-19

☐   Further documents are listed in the continuation of Box C.   ☐   See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 MARCH 1998	1 8 JUN 1998

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